Dynamics & Control

06 March 2012

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Integrity ★ Service ★ Excellence

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2012 AFOSR SPRING REVIEW

NAME: Fariba Fahroo

BRIEF DESCRIPTION OF PORTFOLIO:

Developing mathematical theory and algorithms based on the interplay of dynamical systems and control theories with the aim of developing innovative synergistic strategies for the design, analysis, and control of AF systems operating in uncertain, complex, and adversarial environments.

LIST SUB-AREAS IN PORTFOLIO:

- **General Control Theory:** optimal control, adaptive control, stochastic control, hybrid control
- **Distributed Multi-Agent Control:** path planning, decision making, sensing, task allocation with adversarial and stochastic elements with incomplete information and communication constraints
- **Emerging Applications: Quantum Control, Vision-based Control**
- **V&V of embedded Systems**
- **Mixed Human-Machine Interface**
- **Control of Distributed Parameter Systems**

Key Technology Areas for Autonomous Systems

Autonomy from the Dynamics and Control Point

Key Technology Areas: (from Tech Horizons Report 2010 - United States Air Force Chief Scientist (AF/ST) --Report on Technology Horizons: A Vision for Air Force Science & Technology During 2010-2030)

- Autonomous systems
- Autonomous reasoning and learning
- Resilient autonomy
- Collaborative/cooperative control
- Autonomous mission planning
- Embedded diagnostics
- Decision support tools
- Sensor-based processing
- Human-machine interfaces

Grand Challenges:

- Trusted Highly-Autonomous Decision-Making Systems
- Fractionated, Composable, Survivable, Autonomous Systems

Distributed Control for Networked Systems

A Unifying Theme

- **Objectives:** To address fundamental problems in distributed control of networked systems with non-traditional constraints and adversarial action.
- **Challenges:** A comprehensive research program that deals, within a multi-agents context,
  - with decentralization,
  - localization of objectives,
  - lossy communication and information exchange,
  - incompleteness of information,
  - adversarial interference,
  - multiplicity of objectives,
  - coordination through multi-level interaction.
- **Modeling Framework:** deterministic, stochastic and hybrid structures, cast in discrete- as well as continuous-time settings, with a strong mathematical underpinning.

Key Portfolio Research Challenges

- Autonomous Dynamic Mission Planning : Hybrid System Formulation mix of finite, discrete state (decision variables) and continuous Dynamics, game theory

- Human-Machine Interactions and Operations: dynamics queuing theory for task allocation for human operators, formal models of decision making

- Incorporation of Uncertainty in Mission Environment, Model Parameters: Adaptive Control (L1-Control theory), Stochastic Control

- Adversarial Behavior: Game theoretic Approaches, Stochastic game theory (mean-field theory)

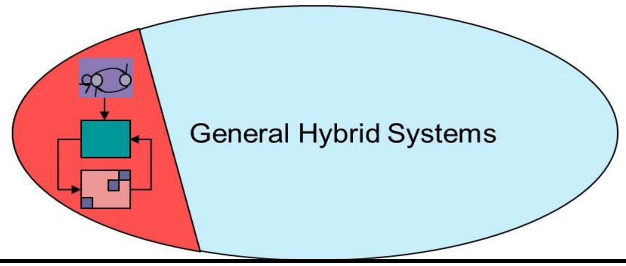
- Incomplete Information: incorporation of learning into games, task allocation, planning

- Computational Issues: Computational Nonlinear Control Theory

- Emergent Applications: Quantum Control, Vision Control

Hybrid Control for Multi-Agent Systems in Complex Sensing Environments

(Geir E. Dullerud, UIUC)



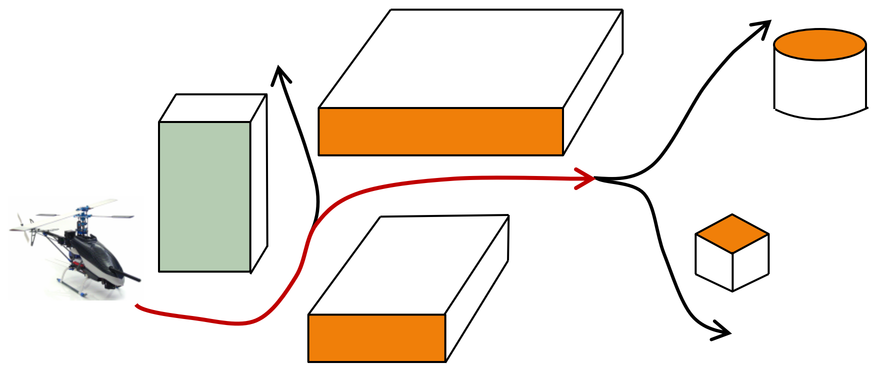
Dynamical model:

$$\dot{x} = f_{\theta_t}(x, u)$$
$$z = h_{\theta_t}(x, u)$$

θ_t state of a specified automaton.
At time t the values $z(t)$ and

$\theta(\tau)$, for *preview horizon* $\tau \in [t, t+H]$

are available for decision making.



Example:

- preview of planned trajectory available out to a finite known future (shown in red).
- governing vehicle parameters known from present to H time units into future.
- strategic objectives known over the dynamic interval $[t, t+H]$.

- **Captures situations where: upcoming environment (e.g., obstacles) can be previewed, for instance via vision-sensing or radar; also scenarios where mission objectives are fixed over a window but evolving.**
- A **hybrid system class** with special structure; this structure can be exploited.
- Result: Provide a complete convex solution (analysis and synthesis) to discrete-time linear model case, for both deterministic and stochastic performance metrics (next chart).
- Form of LTI solution indicates approach for nonlinear case.

Major result: Exact Convex Solution to Linear Receding Horizon Control

Formulations:

Model:

$$x_{t+1} = A_{\theta_t} x_t + B_{\theta_t} w_t$$
$$z_t = C_{\theta_t} x_t + D_{\theta_t} w_t.$$

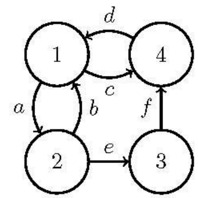
Stability criterion: uniform exponential.
Performance measures treated:

(a) max gain: $\sup_w \frac{\|z\|}{\|w\|}$;

(b) windowed variance: $\sum_{k=t}^{t+H} \mathbb{E}|z(k)|_2^2 \leq \gamma_{\theta_t,\ldots,\theta_{t_H}}$

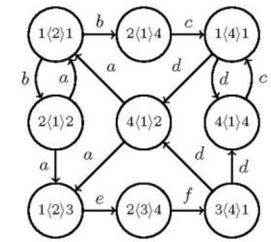
Induced graphs and swtiching paths:

Discrete dynamics governed by a regular language, realized by automaton. More general languages possible.



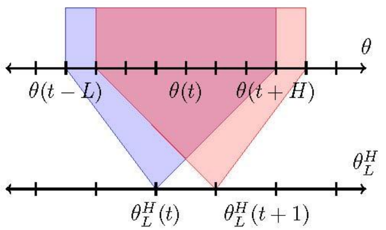
Example Automaton:
1,2,3,4 denote state values θ_t;
transition lables a, b,..., f

Control policy depends on an *induced graph*, based on both future and past automaton paths.



Example Induced Graph:
$\langle k \rangle$ denotes current state;
for case $L = 1; H = 1$.

Optimal solution: feedback policy based on moving window of information, L steps into past and H steps into future.



Solution characteristics

- *provides first solution to 40-year old open problem (solution obtained is actually more general).*
- **Analysis and synthesis problems reduced to convex programming (SDP).**
- **Can design discrete logic: yields a hybrid separation principle.**
- **applies to Markovian jump systems: almost sure uniform stability, almost sure performance.**

Current: nonlinear version via dynamic programming.

2010 MURI (PI: Tamer Başar, UIUC)

Multi-Layer and Multi-Resolution Networks of Interacting Agents in Adversarial Environments

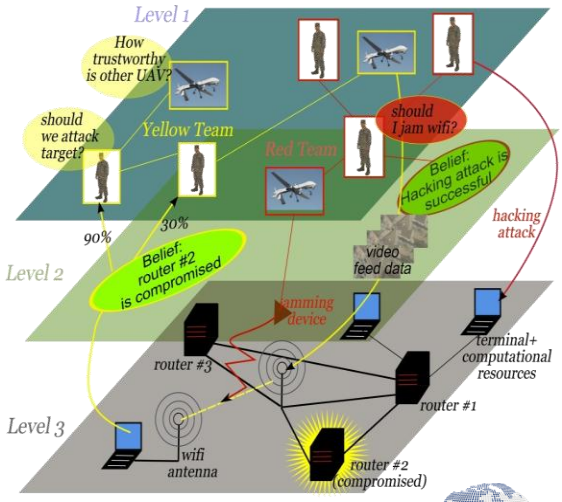
Vision and Overarching Goal:

To address fundamental issues that arise in networked heterogeneous agents, among which are:

complex interactions; *uncertainty* and *adversarial actions*; *trust*, *learning*; *humans-in-the-loop*; *information and communication*; and *design of architectures* to facilitate generation and transmission of *actionable information* for *performance improvement* under different equilibrium solutions.

MLMR Games: Games played at different levels, interacting through their outcomes, action spaces, and costs

"Games within Games": Zooming in and out providing game structures with different levels of granularity



Traditional Model of Decision Making

- A system “controlled” by many agents
- Each agent may have its own objective
- Question: Does an equilibrium or optimal solution exist?
  - Assumptions: The game/team parameters (system, actions, rewards/costs, etc.) are known, computational power is unlimited, and information is not faulty.
- What if some or all of these assumptions do not hold?

Sample Result : Heterogeneous and Hybrid Learning

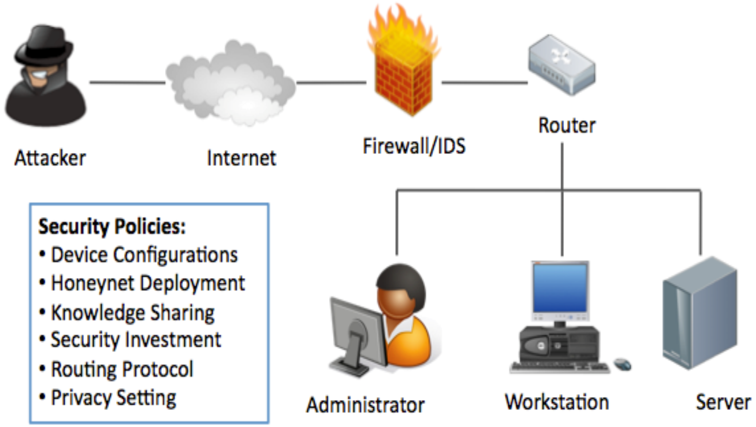
Learning algorithms are essential for applications of game theory in an adversarial environment.

- No knowledge of your own payoff function
- No knowledge of the payoff function of your adversary
- No knowledge of the action spaces of the adversary.

Players have different levels of rationality and intelligence

- Active learner vs. passive learner
- Fast learner vs. slow learner
- Homogeneous learner vs. heterogeneous and hybrid learner

Players do not interact all the time.

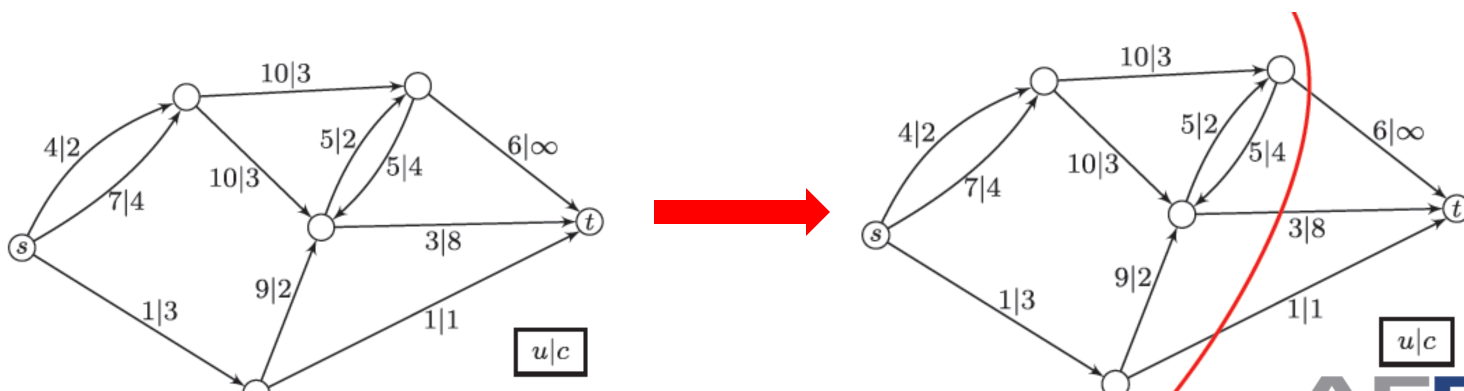


A two-person security game

Result:* *The (Nonzero-sum Stochastic Game) NZSG with unknown states and changing modes admits a state-independent Nash equilibrium.

GIDEANS: Attack and Defense of the Network (D. Castanon, BU)

- **Games where distributed attackers, with *partial information*, attack an intelligent network, also with limited information**
  - **Network adapts its operations to attack outcomes**
  - **Network also may have partial information, distributed intelligence**
  - **Attacks may be “hard” (attrition of components) or “soft” (information corruption or denial)**
  - **Interested in both defense and attack strategies**



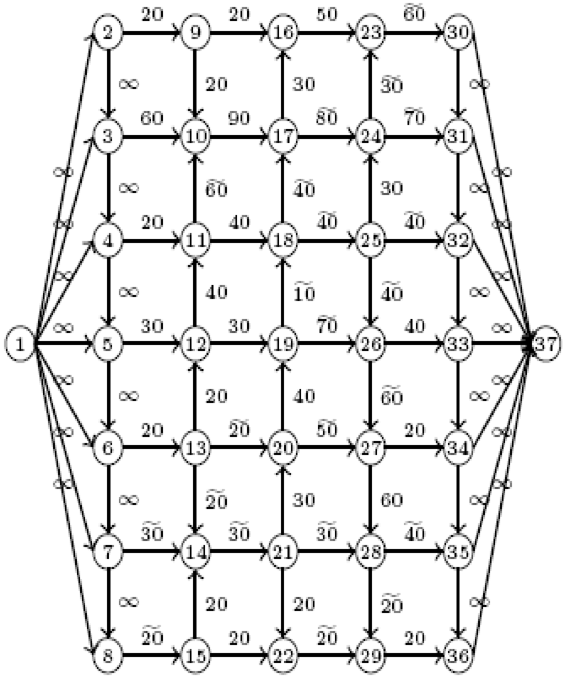
Uncertainty and Partial Information

- **Prior work on stochastic Network Interdiction (Wood et al ’98, ‘02, …)**
  - **Actions of attack have uncertain outcomes**
  - **Outcomes perfectly observed by defender**
  - **Result: Stochastic minimax problem – Stackelberg game**

- **Major Challenges**
  - **Combinatorial complexity for computing strategies even in perfect information case**
  - **Asymmetric information among players leads to difficulties in decomposition algorithms such as dynamic programming**
- **Approaches**
  - **Approximate game analysis and solution techniques based on performance bounds**
    - Stochastic or approximate dynamic programming
    - Minimax performance where network reacts to attacks

Initial Encouraging Results

- **New algorithms for solutions of single stage stochastic network interdiction problem approaches**
  - **Exploits new performance bounds integrated with novel branch and bound search**
  - **3 orders of magnitude faster than previous**
- **New results: algorithms for two-stage attacks for general networks**
  - **Adaptive information exploitation by attacker**
  - **Extension of above performance bounds and search techniques for fast algorithms**



ε-Nash Mean Field Games

Peter E. Caines (McGill U. Montreal)

Overall Objective: Decentralized decision-making for stochastic dynamic games.

- **Large Population Stochastic Dynamic Games:** Large ensemble of stochastic dynamic agents seeking to maximize their individual and collective interest.
- **Key Intuition from Statistical Mechanics:** Extremely complex large population particle systems may have simple continuum limits with distinctive bulk properties.

- Nash Equilibrium Theory for Large Population Stochastic Dynamic Games (4 elements):

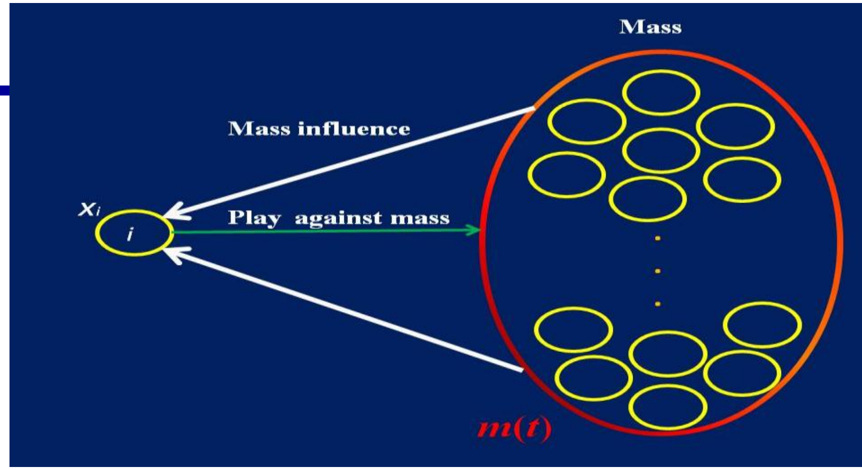
Individual agent systems with cost functions depending on the states of the population

- Element I: Individual Agent Dynamics

$$dx_i = f(x_i, u_i)dt + \sigma dw_i, 1 \le i \le N$$

- Element II: Individual Costs Depending on Mass Behaviour

$$J_i^N(u_i, u_{-i}) := E\int_t^T L(x_i, u_i, x_{-i}^N)ds \qquad V_i := \text{Equilbrium value } J_i$$



Element III: ∞-population Nash equilibrium best response (BR) controls u_i^o given by Mean Field Game (MFG) equations

$$[\text{HJB}]\ -\partial_t V(t,x) = \inf_{u\in U}\left[f(x,u)\partial_x V(t,x) + L(x,u,\mu)\right] + \frac{\sigma^2}{2}\partial_{xx}^2 V(t,x),$$

$$[\text{BR}]\quad u^o(t,x) = \varphi(t,x \mid \mu(t,x)), \quad \mu = \text{generic agent's state distribution}$$

$$[\text{FPK}]\ \partial_t \mu(t,x) = -\partial_x\left[f(x,u^o)\mu(t,x)\right] + \frac{\sigma^2}{2}\partial_{xx}^2 \mu(t,x).$$

Element IV: Apply u_i^o in the finite population game to obtain approximate Nash Equilibrium (as *N* goes to infinity exact NE holds among all the agents).

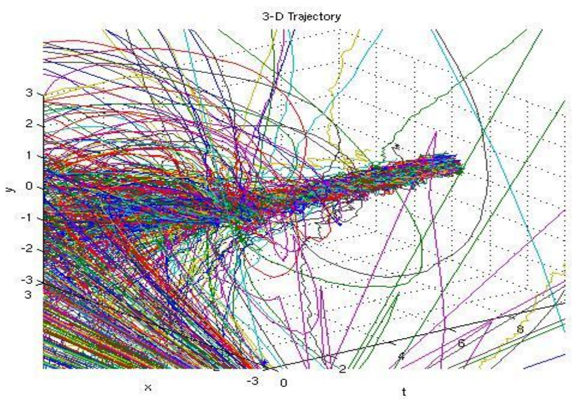
Basic ε-Nash MFG theory and Recent Advances

- **Solution of decentralized decision-making problems with many (minor) competing agents**
- **Key Intuition: Single agent's control = feedback of stochastic local (rough) state + feedback of deterministic global (smooth) system behaviour**

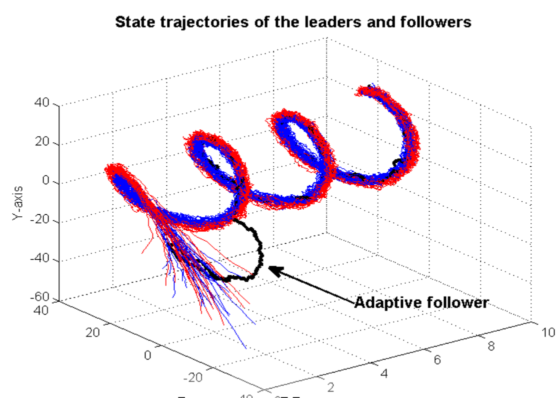
Recent and Current Advances in ε-NMFG Theory (2007-2011):

(i) localized problems in space, (ii) stochastic adaptive **ε**-NMFG control,

(iii) leader–follower systems, (iv) consensus seeking systems, (v) flocking, (vi) cooperative (social) ε-NMFG and egoist-altruist theory, (vii) major-minor agent ε-NMFG theory (Huang 2010), (viii) nonlinear Markov systems theory (Kolokoltsov 2011).



Adaptive **ε**-NMFG



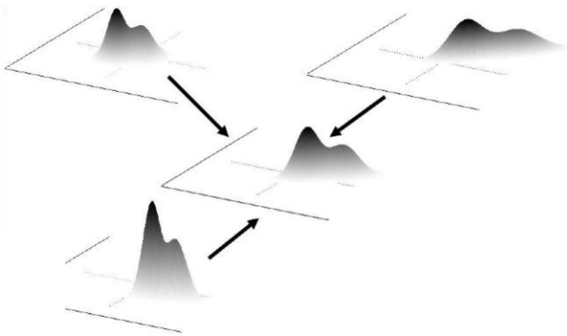
Adaptive Leader-Follower **ε**-NMFG

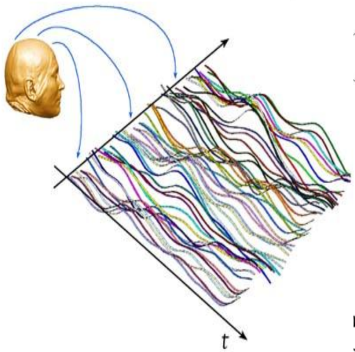
Optimal Mass Transport for Signal Analysis and Control: Tryphon Georgiou and Allen Tannenbaum

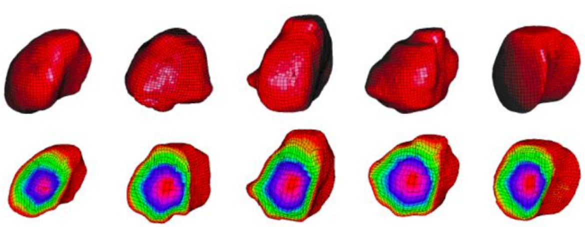
- **Analysis, Comparison, Mixing of <u>Distributions/Masses</u>**

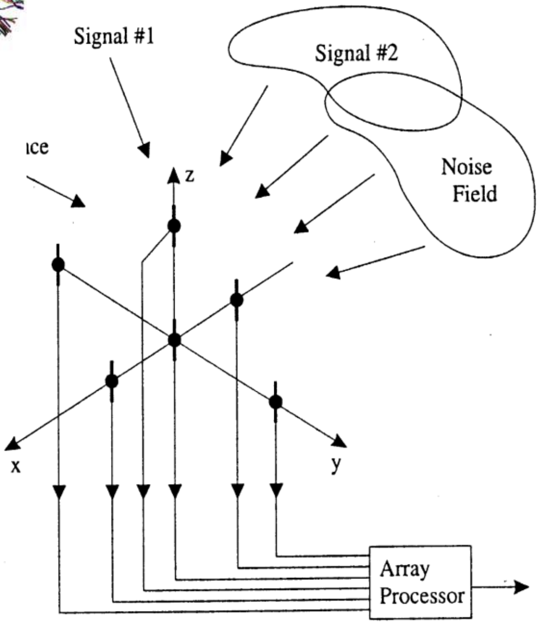
  natural ways to:

  - establish correspondence
  - interpolate, average
  - image/spectra registration
  - intensity/volume preserving



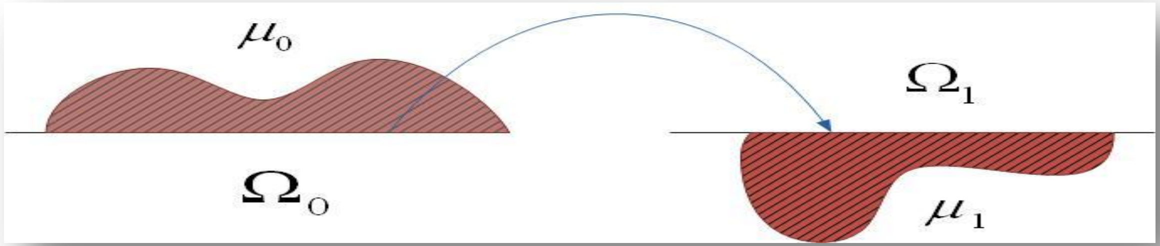






Basic insight

- **Engineer's problem of transporting a pile of soil to an excavation site with the least amount of work**



Optimal Correspondence:

- tools for interpolation, averaging
- metric/geometry on distributions

Leonid Katnorovich received the Nobel prize in 1975 for his work on optimal transport in connection to resource allocation.

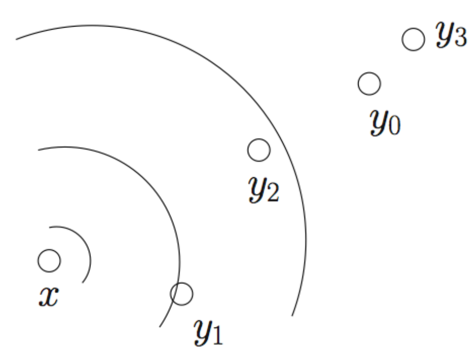
Recent Transitions

Very high resolution methods have been developed

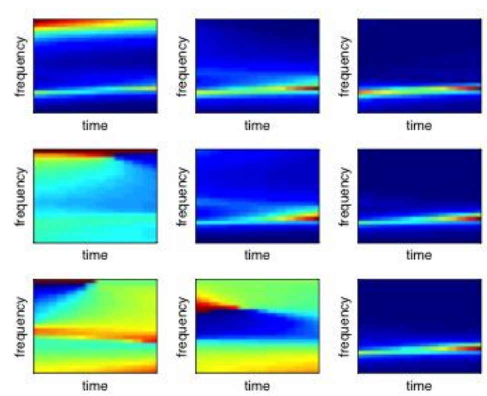
for applications in targeting systems (pointing, detection via antenna arrays)

contact: Dr. Dan Herrick (AFRL/DESA)

Distributed sensor array

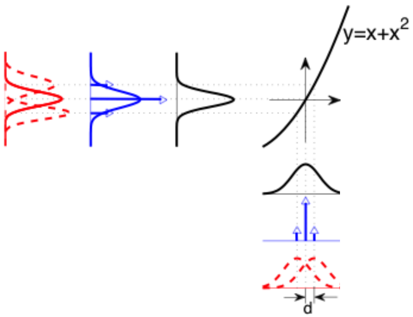


High resolution spatial time-varying spectra
Interpolated via optimal transport geodesics

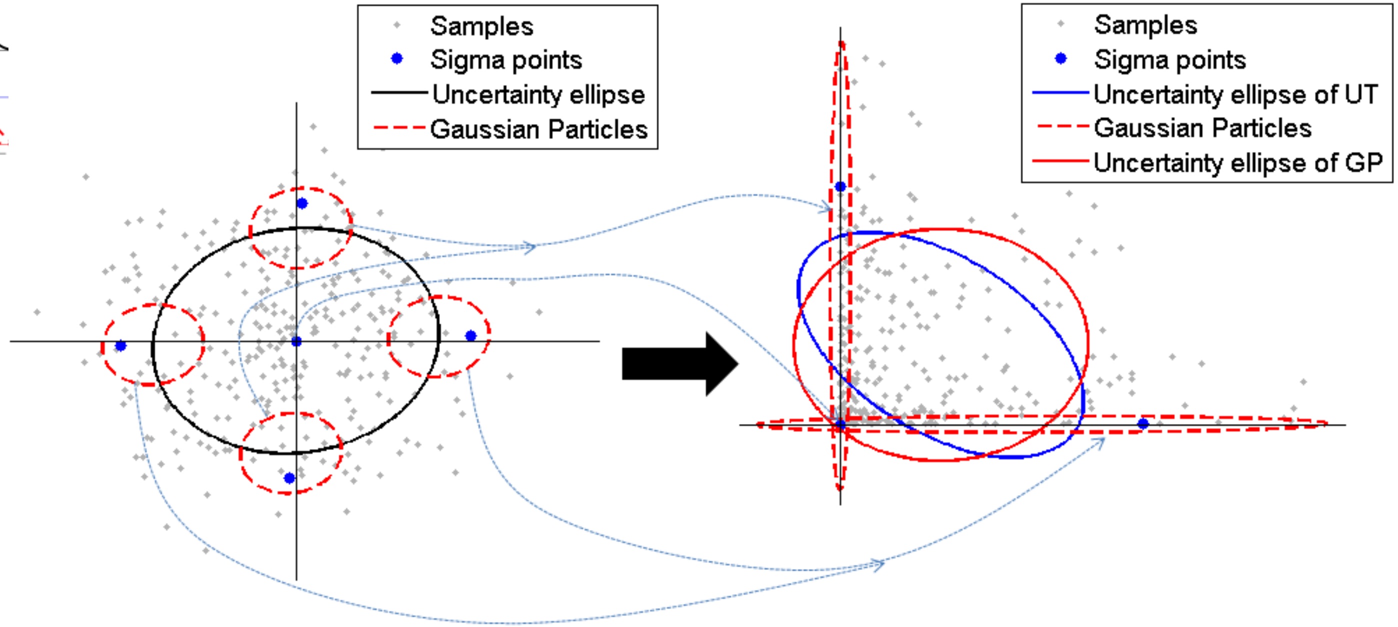


Transformational advances

Optimal transport averaging of distributions lead to new techniques in: estimation, nonlinear filtering



an alternative to Unscented Kalman filter



Robust Dynamic Vision Methods for Persistent Surveillance and Enhanced Vehicle Autonomy

Mario Sznaier (Northeastern Univ)

- Go find something interesting/unusual
- Report only when/what I need to know → Flexible Autonomy
- Take action within given bounds

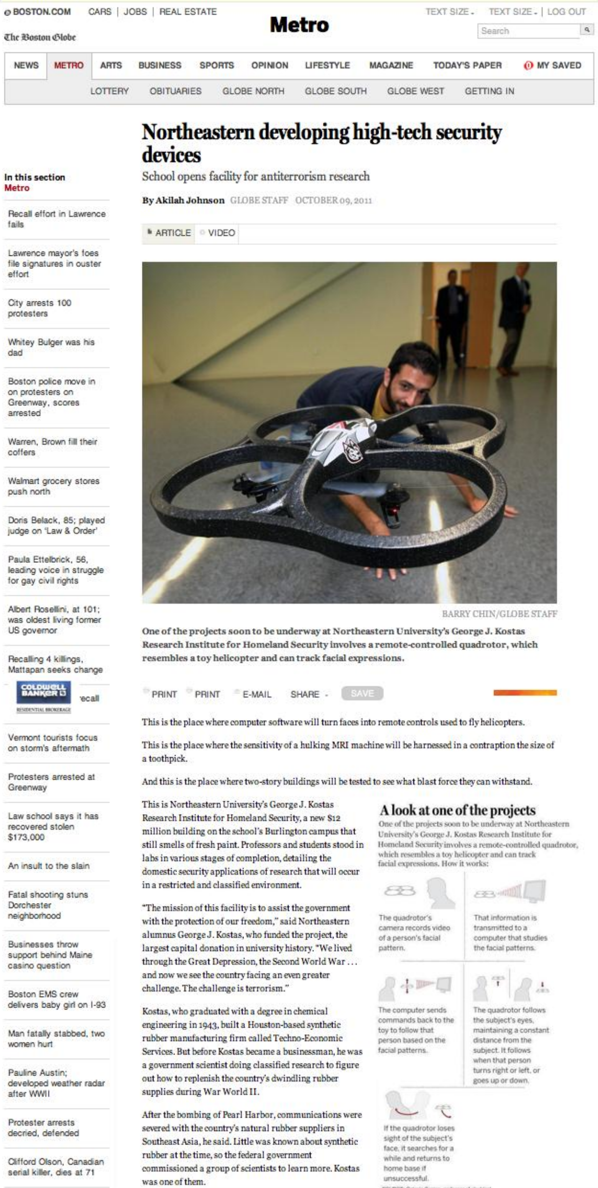
Extracting actionable information from a "data deluge":




In all cases relevant events comparatively rare and encoded in less than $\mathcal{O}(10^{-6})$ of the data

- **Data as manifestation of hidden dynamic structures**
- **Problem can be reduced to identification of hybrid models described by sparse graphs.**
- **Obtain tractable problems by combining dynamical systems, optimization and semi-algebraic geometry tools.**

Success Stories



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LOTTERY OBITUARIES GLOBE NORTH GLOBE SOUTH GLOBE WEST GETTING IN

Northeastern developing high-tech security devices

School opens facility for antiterrorism research

By Akilah Johnson GLOBE STAFF OCTOBER 09, 2011

ARTICLE VIDEO

BARRY CHIN/GLOBE STAFF

One of the projects soon to be underway at Northeastern University's George J. Kostas Research Institute for Homeland Security involves a remote-controlled quadrotor, which resembles a toy helicopter and can track facial expressions.

PRINT PRINT E-MAIL SHARE SAVE

This is the place where computer software will turn faces into remote controls used to fly helicopters.

This is the place where the sensitivity of a hulking MRI machine will be harnessed in a contraption the size of a toothpick.

And this is the place where two-story buildings will be tested to see what blast force they can withstand.

This is Northeastern University's George J. Kostas Research Institute for Homeland Security, a new $12 million building on the school's Burlington campus that still smells of fresh paint. Professors and students stood in labs in various stages of completion, detailing the domestic security applications of research that will occur in a restricted and classified environment.

"The mission of this facility is to assist the government with the protection of our freedom," said Northeastern alumnus George J. Kostas, who funded the project, the largest capital donation in university history. "We lived through the Great Depression, the Second World War . . . and now we see the country facing an even greater challenge. The challenge is terrorism."

Kostas, who graduated with a degree in chemical engineering in 1943, built a Houston-based synthetic rubber manufacturing firm called Techno-Economic Services. But before Kostas became a businessman, he was a government scientist doing classified research to figure out how to replenish the country's dwindling rubber supplies during War World II.

After the bombing of Pearl Harbor, communications were severed with the country's natural rubber suppliers in Southeast Asia, he said. Little was known about synthetic rubber at the time, so the federal government commissioned a group of scientists to learn more. Kostas was one of them.

A look at one of the projects

One of the projects soon to be underway at Northeastern University's George J. Kostas Research Institute for Homeland Security involves a remote-controlled quadrotor, which resembles a toy helicopter and can track facial expressions. How it works:

The quadrotor's camera records video of a person's facial pattern.

That information is transmitted to a computer that studies the facial patterns.

The computer sends commands back to the toy to follow that person based on the facial patterns.

The quadrotor follows the subject's eyes, maintaining a constant distance from the subject. It follows when that person turns right or left, or goes up or down.

If the quadrotor loses sight of the subject's face, it searches for a while and returns to home base if unsuccessful.

SOURCE: Octavia Camps, professor of electrical

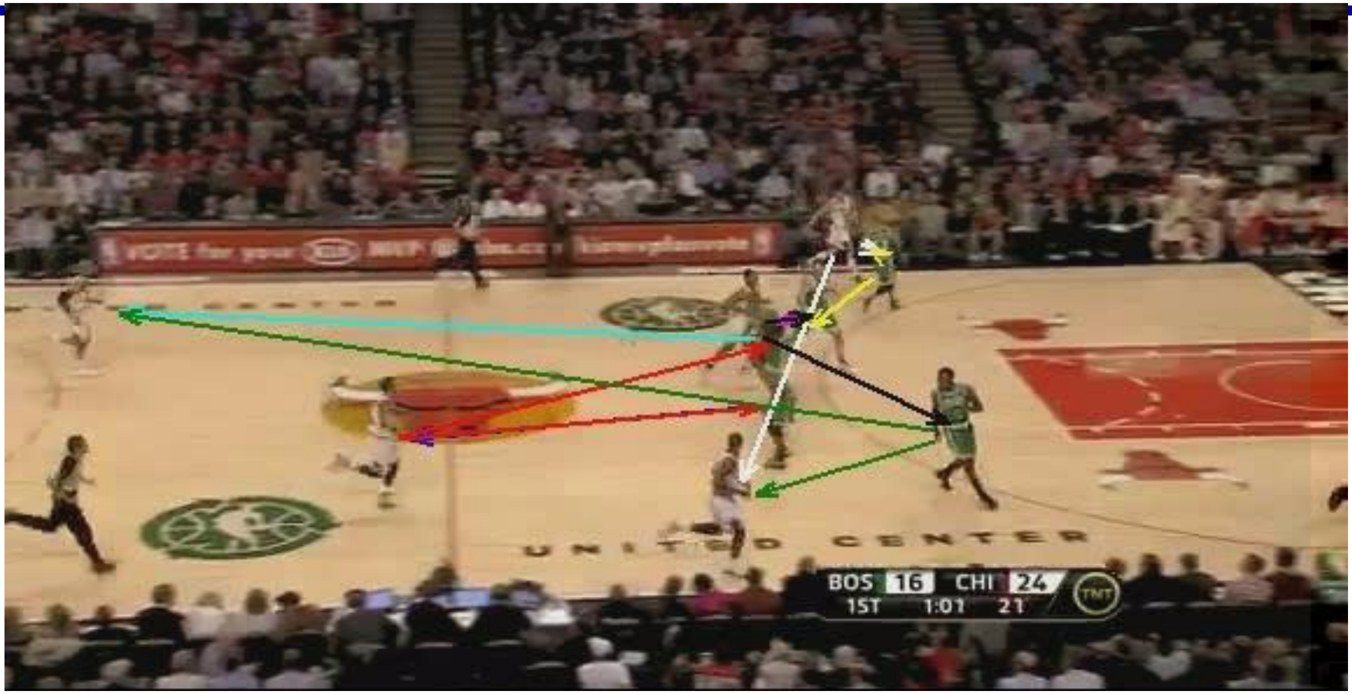
In this section
Metro

- Recall effort in Lawrence fails
- Lawrence mayor's foes file signatures in ouster effort
- City arrests 100 protesters
- Whitey Bulger was his dad
- Boston police move in on protesters on Greenway, scores arrested
- Warren, Brown fill their coffers
- Walmart grocery stores push north
- Doris Belack, 85; played judge on 'Law & Order'
- Paula Ettelbrick, 56, leading voice in struggle for gay civil rights
- Albert Rosellini, at 101; was oldest living former US governor
- Recalling 4 killings, Mattapan seeks change
- ecall
- Vermont tourists focus on storm's aftermath
- Protesters arrested at Greenway
- Law school says it has recovered stolen $173,000
- An insult to the slain
- Fatal shooting stuns Dorchester neighborhood
- Businesses throw support behind Maine casino question
- Boston EMS crew delivers baby girl on I-93
- Man fatally stabbed, two women hurt
- Pauline Austin; developed weather radar after WWII
- Protester arrests decried, defended
- Clifford Olson, Canadian serial killer, dies at 71

A face tracking UAV

http://www.youtube.com/watch?v=z1k4zSFDWnM

Success Stories



Finding correlations in complex scenarios

The "Curse of dimensionality" is a major roadblock in achieving flexible autonomy.
This project takes the first steps towards a *"Compressive Information Extraction"* paradigm:

- Unmanned vehicles
- Flight and perch sensors
- Human in the loop data overload avoidance
- Hitherto unexplored connection between systems identification, information extraction and machine learning

Quantum Linear Systems Theory: Matt James, Ian Peterson

- Why Quantum Control? Is there anything new with Quantum Control?
- Emerging quantum technologies driven by
  - miniaturization (microelectronics, nanotechnology)
  - exploitation of quantum resources (quantum information and computing)

Demand new concepts and tools from control theory at the quantum level

- Classical linear systems theory has a history going back some 50 years, to the birth of modern control theory with Kalman's foundational work on filtering and LQG optimal control. Gaussian Distributions play a fundamental role in classical linear systems theory.
- The PIs have shown that **classical finite dimensional linear systems cannot generate entanglement in a pair of quantum linear systems initialized in a separable Gaussian state → fundamental limitation of classical linear systems when used to control quantum systems.**

Achievements so Far and Need for More Research

- ***Need for new paradigms for quantum stochastics*: non-commutative probability models and a non-commutative stochastic calculus that are not generally studied in the classical setting**
- **Need for new paradigms and techniques for feedback control of quantum systems,** as the classical theory cannot handle the uniquely quantum phenomena (e.g. entanglement)
- This new area in the portfolio started with one grant (Australia), and has continued with a YIP project and a new one in 2011.
- 2011 ARO MURI project. Still there is need for support of more core projects, since the area has the potential of impacting both theory and applications
  - **New methods for using direct physical couplings in optimal coherent feedback system design.**
  - **Differential evolution optimization methods in coherent control of linear quantum systems.**
  - **Decentralized coherent robust H-infinity quantum control.**
  - **Approximation of linear quantum system models.**
  - **Single photon processing by linear quantum systems.**

Summary

- Dynamics and Control is the key enabler in the science of autonomy. There is need for more collaboration with other disciplines: cognitive science, network science, communication, information science
  - New MURI and AFOSR Basic Research Initiative (BRI) topics in V&V, Human-Machine interaction, Control and Synthetic Biology

- Close collaboration and sharing of information with other agencies: ONR, ARO and NSF

- In addition to the core theme of distributed control of multi-agents, the program has solid efforts in control of MAVs, hypersonic vehicles, smart materials and biological systems.

- Support of fundamental research in Control and Dynamics while considering challenging and relevant application areas is what distinguishes this portfolio.